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"Hypersonic Wake Studies"

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I. INTRODUCTION

During the period June 1962 to January 1970, the staff of the Gas Dynamics Laboratory carried out a series of experimental studies to define the characteristics of hypersonic wakes. These fundamental studies of the near and far wake were carried out in a range of Mach numbers from 9 to 16 in a series of facilities using air and helium. A major emphasis of the program was the obtaining of detailed information on three dimensional wakes of "support free" bodies using a combination of a magnetic suspension system and a helium hypersonic wind tunnel. The development of the research might be best characterized with time by the change in emphasis over the period of the contract. During the 1962-64 period, two parallel programs were carried out. Exploratory studies of the wakes behind two dimensional cylinders at Mach numbers of 9 and 16 were carried out at the same time as the development of the magnetic suspension system. The suspension system was completed and put into operation in 1964 and could suspend spheres and conical bodies in a Mach 16 helium stream. In the 1964-66 time period, the major emphasis was on the determination of wake characteristics for spheres and then sharp 10° half angle cones with blunt bases. By 1967 the study was extended to the effect of blunting the cones. In 1968, other geometries were studied. The influence of a hemispherical base on the original blunt based cone configuration and the effect of changing the boundary layer characteristics on the body by "fluting" of the surface were examined. During the last year of the contract, work continued on the hemispherical based model and preliminary work was carried out to extend the studies to higher Reynolds numbers to obtain some preliminary information on the transition in the wake.

The following section of this report reviews the planned research and work statements with brief comments on the results obtained. Ensuing sections review the research results, most of which have been widely disseminated through publications and conference presentations; and finally there is a listing of reports, publications and presentations carried out under the subject contract.

II. REVIEW OF WORK STATEMENTS

The general work statement under which the research was carried out was a "Fundamental Investigation of Near and Far Wakes Behind Various Shaped Bodies at Hypersonic Speeds". The details of the research were determined by results which were obtained during the progress of the program and by numerous consultations with ONR and ARPA representatives. In this section, the general work statement is reviewed by listing the main tasks and the status of research in each area. Further details on each of these items is covered in the following section on "Review of Research Results".

A. Two-Dimensional Wakes.

The primary thrust of the research was on three dimensional bodies but, during the construction of the magnetic suspension system, two dimensional studies at a Mach number of 9 in air and a Mach number of 16 in helium were carried out to supplement other investigations. These studies also helped in the development of the instrumentation required for wake probing. Upon completion of the magnetic suspension system the entire experimental effort was placed on three dimensional bodies and all further two dimensional work was discontinued.

B. The Magnetic Suspension System - Hypersonic Tunnel Development.

The magnetic suspension system provided an important and rather unique contribution to the studies over the subsequent years. Although the suspension system was never brought to the state of development where any configuration could be flown without difficulty, the work on the suspension system was continued to the point where spherical and conical models could be flown consistently under the desired test conditions (a Mach number of 16 and a Reynolds number of approximately 120,000 per inch). After the original development, only such minor modifications to the system as were required for the tests that were planned were carried out. Although considerable further work would have been valuable for the general development of the system, it was felt that it would not have contributed significantly to the capability to do the work under this contract. The hypersonic helium tunnel used in these studies was an extension of previous experience of the Gas Dynamics Laboratory and required no new developments.

C. Sphere Wakes.

Studies of the wakes of spheres, the first body tested using the magnetic suspension system, were carried out to the point where full analysis of the results showed that far wake results could not be obtained because of the interaction of the strong bow shock with the tunnel wall boundary layers. Since the purpose of the program was to study both near and far wakes, the work on spheres was discontinued and the primary emphasis was then placed on conical bodies.

D. Transition Studies.

One of the main results obtained from the spherical body tests was that transition did not occur although the program had been designed to study transition. It was found that no transition occurred within the test region and it was estimated that transition occurred at about a factor of 3 higher than had been observed in firing ranges. Preliminary results of hot wire surveys behind spheres with some comments concerning transition are noted in the following sections along with some preliminary results obtained at high Reynolds numbers on cones.

E. Sharp and Blunt Cone Wakes.

Studies of the wake of a sharp 10° cone were completed. The subsequent study of the effect of bluntness on the same cone varying the configuration from a sharp cone to one with a nose radius 20% of the base radius also was completed. Possible extension of this work to small angle of attack and non-symmetric bodies was not carried out when analysis and preliminary studies showed that significant modifications to the magnetic suspension system would have to be accomplished to permit such studies.

F. Low Density Studies.

Although early proposals considered extending the present work to a very low density, the detailed examination of the wake showed that the core of the wake was already in a density regime where major viscous effects predominated. Although some exploratory studies were carried out in a few tests to determine the requirements for using the magnetic suspension system on a hot nitrogen facility to provide much lower densities, the program was not pursued because of lack of interest by ARPA.

G. Surface and Base Geometry Effects on the Wake.

The examination of body geometry on the wake flow covered the range from a sphere to a sharp cone to a blunted cone. Extensions of these studies to a cone with a hemispherical base to evaluate base geometry effects, and also to a sharp blunt based cone with a fluted surface to determine the effects of varying the boundary layer were undertaken during the last 18 months of the subject contract. Preliminary tests of a fluted cone and the first phase of the hemispherical based cone study were completed, although neither of these two studies are complete enough for publication. Further studies on both of these geometries are required, although the available results have been disseminated to interested parties.

H. Wire Support Effects.

The magnetic suspension system provides a completely support-free body which, in a wind tunnel, is as close as one can come to free flight. A few studies were carried out to examine the effect of physical supports, although no major effort was placed on this study. Wires supporting spheres were found to cause considerable disturbances in the wake. Plans to repeat these tests on cones were not completed, although planned for under the subject contract.

I. Effects of Mach Number, Reynolds Number, and Surface Temperature.

The effect of variable Mach number, Reynolds number, and surface temperature on the detailed wake studies obtained for sharp and blunted cones were not carried out although considerable discussion took place with regards to the importance of such tests. The present facility-magnetic suspension system combination did not permit very wide variations in Reynolds number, without significant modifications. As a result, most of the experiments were carried out under a single set of test conditions, Mach number 16 and a Reynolds number of approximately 120,000 per inch. Mach number variations could have been carried out by changing to a different nozzle configuration, but this assumed low priority in the present program and was not attempted. Extension of the present results to high Reynolds numbers were attempted during the last phase of the contract using whatever equipment was available and operating the facilities in a range not heretofore attempted. Preliminary results were obtained on what appeared to be transition in the wake. The general characteristic of the disturbances forming an annulus around an undisturbed core supported earlier results obtained from the sphere. Plans for tests of a model to test surface temperature effects were put aside when the required modifications to the suspension system could not be financially supported. Preliminary tests showed that a heavy copper model could be pre-chilled for the tests, but the added weight of this model, as compared to the basic model, required a change in the suspension geometry.

III. BRIEF REVIEW OF RESEARCH RESULTS

In the following section, the research results obtained from the subject contract are reviewed. Since most of the work is available in published form and has been discussed in detail with those groups directly involved in wake calculations and research, the comments will be brief.

1. Two-Dimensional Wakes

During the early phase of the subject contract, while the magnetic suspension system was under construction, two studies were carried out on the two dimensional wakes behind cylinders. One of these was carried out at a Mach number of 16 in the helium facilities[1,5], the other at a Mach number of 9 in a small hot air facility[2,7]. These studies extended downstream approximately 50 body diameters and used cylinders approximately a tenth of an inch in diameter. The results provided an extension of two dimensional data at lower Mach numbers. The rate of growth of the wake was about equal to that found at the lower Mach numbers and there appear to be no dependence of wake growth on either Mach number or Reynolds number. It was also found that it was not possible to determine transition from the pitot pressure surveys alone, and no longitudinal pressure variations or discontinuities were found over the entire length of the wake. The wake decay, (diffusion of the inner wake), was shown to be an exponential decrease in the pitot amplitude with increasing wake length.

2-A. Magnetic Suspension System.

The development of the magnetic suspension system was one of the key achievements of the early part of the program. Although the French had previously shown proof of the concept, the system built at Princeton (using inputs from studies being carried out at both Virginia and AEDC) resulted in a system which was a significant step forward in this area. References 3, 6, 8 and 9 detail the development of the balance. Major work on the balance was completed in 1965 and only small modifications were made since then to take into account the variations in geometries and test conditions during the latter part of the program.

The suspension system was of a rather unique geometry. By mounting the tunnel vertically, the suspension system could be made symmetric. The magnetic geometry chosen uncoupled the magnetic forces of the drag components from the stabilization forces. The suspension system was designed only to satisfy the requirements to suspend axisymmetric bodies, starting first with a sphere and then extending to cones. The cones, however, were non-magnetic shells with an embedded magnetic sphere as the only active component in the system. The magnetic suspension system very satisfactorily supported spheres of 3/8 and 3/4 inch diameter, 10^{o} cones of 3/4 inch to 1 1/2 inch diameter, and cones of 1 inch base diameter blunted to 20% of the base diameter. Some difficulty was experienced supporting a fluted cone and considerable difficulty was experienced supporting the cone with the round base. This latter problem appears to be due to non-symmetric separation over the base and the generation of significant side forces. Since the system was designed for only small side forces, fully satisfactory operation for this configuration was not obtained although it is believed that the balance could be modified to take care of this problem. The concept of the magnetic suspension system proved to be completely workable. An unforeseen difficulty in only one area of research developed toward the latter part of the program. Because of the magnetic field, instrumentation such as electron beams can not be used in this system. Correlation between models on physical supports in a similar facility without the magnetic field and tests with other instrumentation in the magnetic field were required to make use of the special characteristics of the electron beam.

2-B. Hypersonic Tunnel Development.

The hypersonic tunnel used in the present studies is a direct model of a facility in operation under support from the Aeronautical Research Laboratory. The tunnel uses pure helium as a test fluid and can generate Mach numbers from the 8 to 20 range. A Mach number of 16 was chosen for the present tests. A special long test section was designed to permit the study of the development of the wake behind the test body in a uniform region. Since optical windows had to be installed in this test region (for the light screen detection system required for the magnetic suspension system), the model was "flown" downstream of the nozzle exit in comparison to the usual use of the forward half of the test rombus in ordinary aerodynamic testing. The final configuration used was a test section of approximately 7 inches in diameter which resulted in a uniform test core of about 4 inches in diameter extending about 15 inches downstream of the model mounting position. The facility and its details were described in Reference 4.

3. Study of Sphere Wakes.

The first studies of three dimensional wakes started with examining the wake behind a sphere. This geometry was chosen because of the availability of results in firing ranges and the simple symmetric geometry. The test model consisted of a Ferrite sphere. Originally the test model was 3/4 inch in diameter but subsequent results showed the need for a smaller sphere and modifications to the system permitted spheres of 3/8 inch diameter to be flown. Details of this study were presented in Reference 4 where the results were compared with theories and two dimensional experiments. Wake width data agreed well with the ballistic range results in the Mach number 10 range and were substantially above the ballistic range data obtained at lower Mach numbers. One of the most interesting results was the fact that hot wire studies of the wake suggested that the flow was completely laminar, although extrapolation from free flight results indicated that transition should have occurred within the examined region. More important, the hot wire surveys indicated for the first time a structure of transition or disturbances which was annular; that is, disturbances were found at the outer edge of the wake but not within the central core. Subsequent studies of the differences between the wakes of the two diameter spheres showed that the general flow field downstream of the spheres was influenced by the interaction of the strong bow shock and the tunnel walls and boundary layer . As a result, further studies were deferred and efforts were concentrated on conical bodies whose bow shock structure caused no interference in the region of interest.

4-A. Study of Sharp Cone Wakes.

The modification of the suspension system to permit the study of the wake behind cones was accomplished with no major difficulty. A non-magnetic shell, made of copper or tantalum and nylon, was used for the exterior shape while a magnetic sphere (similar to the sphere model flown in the original study) was imbedded within the model at a location which provided an aerodynamically stable configuration under test. Most of the cone studies were carried out with the body of 1 inch base diameter, providing a test region behind the body of about 15 diameters. The only problems associated with the tests were "roll resonance", a phenomena which was found to also influence actual test vehicles. It results from slight misalignments of aerodynamic and geometric centers. Satisfactory results were obtained with quality control of the models and the simple discarding of models which spun during tests. The major efforts since 1965 have concentrated on conical models of various geometries. The results on sharp cones have been presented in detail in References 10, 11 and 15. These tests have resulted in the detailed presentation of the physical properties of the laminar hypersonic wake behind such a body, extending from the base region to 15 diameters downstream. The results showed that the near wake was completed within about 5 body diameters. Downstream of this region, which included the separated region, the stagnation point, the throat, and the trailing shock structure, the wake remained at approximately constant diameter within the test region with negligible variations in pressure across the wake. The detailed measurements provided a full model of the flow upon which to check the several numerical methods of predicting such flows. The key characteristics of the hypersonic wake was that the density changed by over two orders of magnitude going from the edge of the wake to the center of the wake while the velocity within the wake accelerated quickly to approximately 80% of the free stream. The general structure of the wake was one of major density differences rather than major velocity differences. The mixing rates were extremely small. The very wide variation in unit Reynolds number across the wake caused the main problems in the instrumentation. Considerable difficulties were experienced in examining these flows since the range of conditions covered was much greater than heretofore experienced. Redundant techniques using instrumentation of many types were required. Results from total head tubes, static pressure tubes, hot wire anemometers, heat flux meters, and mass flow probes, were used to cross-check measurements to prove validity of the final results. Detailed examination of the flow field as probing took place within the separated region showed that probe effects could not be eliminated within this region. Therefore, most of the results obtained were concentrated on obtaining the full structure of the flow rather than on details within the recirculation region. Determination of the stagnation point, sonic areas, and the full structure of the trailing shock and definitions of the near and far wake were completed.

4-B. Study of Blunt Cone Wakes.

As a direct follow on to the sharp cone studies noted above, the primary geometrical factor examined was the effect of nose bluntness on the wake structure. The studies of the sharp cone were repeated with nose bluntnesses varying from the sharp to bluntnesses of as much as 20% of the base diameter. These results were presented in References 12, 14 and 16.

Improvements in instrumentation, which accompanied these latter studies, gave even more precision to the results which were obtained. In general, although details within the wake structure were changed, the overall phenomena was not much influenced by bluntness of the degrees studied. Further verification and detail of the wake structure was obtained and hot wire work confirmed that the wake was entirely laminar throughout the region studied, although some disturbances were measured along the outer edge of the wake. This reinforced the concept that transition, when it did occur, must occur in an annular region surrounding the outer edge of the wake. The differences between the unit Reynolds number in this outer region and in the central wake were two orders of magnitude and the concept of transition occurring across the wake seemed to be completely unreasonable.

5. Other Cone Studies.

It was hoped to extend the work on sharp and blunted cones to examine several key parameters in wake development. Examination of the wake on these bodies at a significantly different Reynolds number, but still laminar, was proposed; but within the limitations of the present contract it could not be carried out. The facility, in its basic form, provided only a relatively small Reynolds number variation by changing stagnation pressure. In an attempt to obtain some idea of the influence of the change of boundary layer characteristics on the body on the wake development, a preliminary study was carried out with a sharp cone with its surface fluted along rays of the cone. Fluting accomplished a doubling of the thickness of the shear layer at the base of the cone without disturbing the external inviscid flow field. Results of this study were presented in Reference 13. Although these studies were of a rather preliminary nature, they showed a definite thickening of the wake but no significant changes in the overall characteristics. The trailing shock was more diffuse but the major density changes across the wake were approximately the same as that for the case of the smooth surface cone. Preliminary work was also started on a sharp tipped cone with a hemispherical base. These experiments were undertaken to examine the effect of this shape on the wake structure and to permit a comparison with theoretical predictions which require a priori a knowledge of the separation point. For the flat based models the sharp rear edge provides the point of separation, whereas the radius of curvature of the hemispherical base model is substantially larger than the boundary layer thickness and provides a test of a different theoretical treatment. Moreover, a two-dimensional model with a cylindrical base has been tested at lower supersonic speeds. It was hoped that a comparison of these data might shed additional light with regards to two-dimensional versus axisymmetric studies and to further evaluate Mach number effects. Unfortunately, the full range of intended measurements could not be completed under the subject contract. Unexpectedly large side forces obtained with the model in the magnetic suspension system were beyond our existing instrumentation capability. Only a few preliminary results were obtained before the contract concluded. In spite of the substantial difference in base geometry, the center line base pressure was nearly exactly the same on this model as that of the flat base model. The minimum pressure measured on the base, relative to the center line pressure, was markedly smaller than that of the two-dimensional low Mach number experiments, and occurred appreciably closer to the center line. In contrast to the two-dimensional results, furthermore, practically no constant pressure region was observed on the base. These observations suggested the boundary layer over the hemispherical base, expanding more gradually than on the flat base, eventually separates from the surface in the region fairly close to the center line. As a result, the re-circulation regions is quite small. Limited pitot pressure surveys substantiated these results. The pitot pressure bucket behind the body is somewhat deeper and broader than for the blunt base, the separation shock is initiated more gradually from the separation region and is definitely weaker than for the blunt based configuration. Considerable further work is required to fully clarify the differences between the hemispherical based model and the flat based one, and such studies require some modifications to the existing facilities.

6. Preliminary Results at High Reynolds Number.

Near the completion of the present contract, some exploratory tests were carried out at a considerably higher Reynolds number to examine whether any indications of transition to turbulent wake flow could be obtained. Operation of the facility was carried out at almost three times the stagnation pressure used for the present studies, resulting in a unit Reynolds number of about 300,000 per inch compared to the 120,000 of the basic tests reported above. Exploratory hot wire studies of the wake were carried out but it should be noted that the flow quality in the test region was not at the same level as for the original tests. The higher stagnation pressure requires a modification to the nozzle to obtain the uniform flows obtained at its design conditions. Although there were variations of Mach number within the test area, it is not believed that they had a primary effect on the results which were obtained. The results showed that, at higher Reynolds numbers, significant non-steady components were found at the edge of the wake regions. The non-steady results obtained by the hot wire extended over only a very narrow region at the outer edge of the shear layer. The central core of the wake remained completely disturbance-free, as indicated by these preliminary hot wire studies. The results are quite analogous to the examination of the turbulent boundary layers on the walls of the facility, where large fluctuations are restricted to a very thin layer near the outer edge of the boundary layer (the core of the wake corresponding to the lower part of the boundary layer). These preliminary results have formed the basis for our new proposal in this area, but considerable further work and refined measurements are required before any definite conclusions on the structure of the wake at high Reynolds numbers can be completely supported. The concept of an annular region of fluctuations or turbulence surrounding a quiescent low density core appears, however, to be substantially supported as it was originally proposed from the early work on spheres.

7. Other Incompleted Studies.

Although it had been hoped that some time could have been put on the examination of the interference caused by wire supports of models (a technique used by other investigators), only the early results on spheres were obtained. For spheres, significant disturbances of the wake flow were measured and considerable differences in the structure of the flow between support-free and wire supported spheres were obtained. However, it should be noted that these results cannot, in general, be extrapolated to wire supported conical models. The boundary conditions on the models were quite different as well as the external flow fields. Further work is required before a full evaluation of the effect of wire supports on conical models on both the near and far wake can be evaluated with confidence. Proposed studies of surface temperature effects, non-axisymmetric configurations, and non-zero angle of attack configurations could not be undertaken within the present contract primarily because of difficulties associated with flying more complex shapes on the present magnetic suspension system without significant modifications.

IV. CONCLUDING REMARKS

The basic purpose of the subject contract, the providing of the detailed information on the hypersonic wake behind axisymmetric bodies of several geometries, has been accomplished. The results are of sufficient accuracy and detail to permit the checking of the "pure gas" part of the several numerical methods used to calculate such wake flows. Although preliminary results were obtained for many of the other parameters which might be of interest, considerable further work has yet to be done before a complete picture of the wake flow can be presented with confidence that all of the key parameters have been included.

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